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CORAL REEFS AND SUBMARINE BANKS

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PART II

Fundamental postulates of the glacial-control theory.—If we now return to the consideration of the principal postulate of the glacial-control theory, it should be noted that the features appealed to in evidence of long-enduring ocean-bottom stability are not directly concerned with the deep ocean floor itself, for the ocean floor is inaccessible to geological observation; nor do they concern the geological structure of islands with elevated reefs which give a decipherable record, for nearly all of these islands seem to have had elevations and subsidences during their long history. The glacial-control theory is chiefly concerned with atolls and submarine banks, the history of which is not directly decipherable; and the features which are taken to demand long-enduring crustal stability are, as already noted, the nearly level floors and the similar and moderate depths of atoll and barrier-reef lagoons and of submarine banks, although they are all covered with unconsolidated calcareous deposits of recent deposition and unknown thickness.

In seeking to account for these well-substantiated submarine features, the glacial-control theory advances reasons for thinking that the nearly level lagoon deposits must be of small thickness and must therefore rest on nearly level rock platforms at a moderate and fairly uniform depth in all the coral seas. It is next argued that the production of the inferred rock platforms was preceded by subaërial erosion and marine abrasion during a long preglacial period of "general crustal stability in the coral sea," whereby lofty volcanic islands were worn down to insular lowlands. Then, in view of the plausible inference that reef-making corals were killed during the glacial period, it is further supposed, as previously outlined, that the chilled and lowered ocean was free to cut away the dead reefs and to reduce the worn-down islands to flat platforms. Finally, as the ocean rose and warmed in postglacial time, the existing reefs are believed to have grown up around the platform margins, while unconsolidated calcareous deposits were strewn evenly over the platform surface; or, if reefs did not grow up, the platforms remained as submarine banks.

The ingenuity with which the successive conditions and processes are enchained is certainly admirable, but the fundamental assumptions do not seem to be fully established, and the conclusions reached are not unescapable. The links of the chain of argument must be separately examined. The plausible inference that reef-making corals were killed during the glacial period will be considered in the next two sections.

Coral reefs not destroyed during the glacial period.—It is certainly plausible to suppose that reef-building corals may have been killed by the lowering of oceanic temperatures during the glacial epochs of the glacial period, but no sufficient tests of the correctness of this supposition have been brought forward. As far as I have been able to analyze the question, the reefs were not so completely divested of protecting organisms, except along the margin of the coral zone, as to expose them and their inclosed islands to abrasion, for the consequences of such abrasion are not found in the expectable form of spur-end cliffs (*KN*, Fig. 3*b*) on the central islands of fringing or of close-set barrier reefs, as I have elsewhere pointed out;[1] hence this essential element of the glacial-control theory lacks support. The previously stated arguments which lead to this conclusion need not be repeated here, but additional evidence to the same end may be presented from Hawaii, Tahiti, and Murea.

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[1] "A Shaler Memorial Study of Coral Reefs," *Amer. Jour. Sci.*, XL (1915), 223–71; see pp. 236–46. "Problems Associated with the Study of Coral Reefs," *Sci. Monthly*, II (1916), 559–77.

Evidence from Hawaii, Tahiti, and Murea.—Let it first be noted that Hawaii, Tahiti, and Murea are three of four islands—the other is Rotuma, north of Fiji—which Daly instances as having "submarine benches so narrow as to prove the extraordinary power of fresh lavas to resist the Pleistocene breakers" (182). Rotuma I have not seen, but Gardiner's account of it[1] suggests that the narrowness or absence of an abraded bench around it may be due rather to the recency of its latest lava flows than to their resistance. Hawaii also was not reached during my voyage of 1914, but Branner's account of it[2] and the several excellent topographic sheets recently published by the United States Geological Survey of its northern and northeastern coast give good reason for thinking that the general absence of a cliff-backed bench around its shores is due to the recency of the eruptions that have covered most of its slopes with lava flows in which valleys are not yet eroded; while the occurrence of deep consequent valleys and strongly clift intervalley spur ends in the Hamakua district of the northeast coast gives equally good reason for regarding that part of the island as much older than the rest—old enough in fact to have suffered submature dissection and mature abrasion, but at a time when the island stood several hundred feet higher than now, as Branner has so well shown. By constructing longitudinal sections and cross-sections of the great valleys from the topographical maps, I have inferred that the amount of submergence since the valleys were cut down and the cliffs were cut back is some 800 feet. But whether submerged or not, the island of Hawaii ought not to be instanced in proof of the belief that the absence of spur-end cliffs on the central islands of barrier reefs elsewhere in the Pacific is due to the resistance of their lavas: to my reading Hawaii supports the other side of the discussion, namely, that volcanic islands which are indented by drowned-valley embayments half a mile or a mile wide must, like northeastern Hawaii, have had strong cliffs cut in their spur ends if they were exposed to abrasion during the considerable period required for the erosion of the now drowned valleys; and as such cliffs are prevailingly absent on reef-encircled islands the islands must have been protected from abrasion—that is, their reefs must have been clothed with growing organisms of some sort—while the now drowned valleys were eroded.

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[1] J. S. Gardiner, "The Coral Reefs of Funafuti, Rotuma, and Fiji . . . . ," *Proc. Cambr. Phil. Soc.*, IX (1898), 417–503.

[2] J. C. Branner, "Notes on the Geology of the Hawaiian Islands," *Amer. Jour. Sci.*, XVI (1903), 301–16.

Tahiti gives even stronger evidence to the same end. This island consists of a larger and a smaller volcanic cone, joined in an isthmus. The slopes of the cones are submaturely or maturely dissected by deep, steep-sided, radial valleys, the lower ends of which have been embayed by submergence after they were eroded; but the embayments are now, with few exceptions, filled with deltas which have expanded outside of their embayments so as to form a continuous alluvial belt around much of the shore line; it was this "broad belt of low land at the foot of the mountains" which Darwin properly interpreted as indicating "a long stationary period" for Tahiti. It is, however, not the radial valleys but the spur-end cliffs that are the most significant feature of Tahiti in the present connection. Agassiz gave a good account of them. Some of the cliffs rise 500 or 1,000 feet above present sea-level on the more exposed coasts; but the northwestern or leeward corner of the island is without visible cliffs for a short distance. Their origin must have been contemporaneous with the erosion of the valleys; hence the base of the cliffs and the platform that must have been abraded at a small depth below sea-level when the cliffs were cut back must be now, like the distal portion of the valleys, submerged. The depth of submergence, inferred from the cross-section of some of the larger valleys, may well be 500 or 600 feet; the lagoon, much aggraded, is naturally of less depth.

It is immaterial for the moment whether the opportunity for cliff-cutting around Tahiti was given while the ocean was chilled and lowered in the glacial period, or whether it was given while the island stood higher and was, like Reunion, reefless because a sheet of shore detritus prevented coral growth, as I believe is the more probable explanation.[1] The lesson to be learned here is that the time which sufficed for the erosion of the steep-sided valleys of Tahiti sufficed also for the cutting of its great cliffs; hence, far from proving the power of fresh lavas to resist the breakers, Tahiti proves that, resistant as its lavas may be—and they certainly look very resistant where ledges are exposed in the cliff faces and on the valley sides—the waves of the trade-wind sea can strongly abrade the coastal slope of a volcanic island in the same period of time that is needed for the erosion of submature or mature valleys; and that the spur-end cliffs thus formed may be of such height that they will still rise hundreds of feet above sea-level after the cliff base and the platform in front of it and the valley ends between the clift spur ends are submerged hundreds of feet below sea-level. It therefore still seems to me reasonable to be guided by the conclusion elsewhere set forth that the general absence of spur-end cliffs in the central islands of close-set barrier reefs and especially in islands like Rarotonga, that have only a fringing reef, contradicts the assumption that reef-building corals were killed and that the islands that they normally protect were exposed to abrasion during the glacial period.

In order to avoid misunderstanding, let it be added that many spur ends of reef-encircled islands are nipped off in low, freshly cut bluffs, 5 to 30 feet in height, and that these low bluffs are fronted by wave-swept rock platforms of small breadth visible at low tide; hence these bluffs and platforms must be ascribed to wave work of the lagoon waters now or recently in progress at present sea-level. Further, let it be noted in passing that the subsidence inferred for Hawaii must have taken place while its gigantic young cones were in process of formation by eruption; and that a subsidence of Tahiti during its eruptive growth is also suggested, but less definitely, by its association with its more submerged neighbors. These two instances deserve consideration as antidotes to the prevailing idea that volcanic eruption is necessarily associated with upheaval. It is eminently possible, if not probable, that the reverse relation may often obtain, and still more possible that subsidence may set in shortly after eruption ceases.

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[1] "Clift Islands in the Coral Seas," *Proc. Nat. Acad. Sci.*, II (1916), 284–88.

Murea, near Tahiti, may be briefly considered. Its dissection is far more advanced than that of Tahiti; its slopes are less steep, its embayments are much larger and wider; several spur ends of its northwest or leeward coast are rather strongly truncated in sloping facets resembling mature cliffs, but around most of its circuit the spurs descend gradually to sea-level; the barrier reef here is comparatively close-set. Surely, if the great cliffs of Tahiti were cut under the conditions assumed in the glacial-control theory, great cliffs should have been cut at the same time around Murea, especially on its southern and eastern sides; the absence of such cliffs indicates that the sea has not had access to the island shore, or, in other words, that the encircling reef of Murea has long protected the island from abrasion. The absence of cliffs cannot be explained under the glacial-control theory by postulating an exceptional resistance for the lavas of Murea; for if the total duration of lowered sea-level during the glacial period were long enough for small streams to deepen their valleys and for the slow processes of weathering to widen the deepened valleys to the form now seen in the drowned-valley embayments in spite of the exceptional resistance postulated for the island lavas, then the waves of the lowered sea working through the same duration of time should all the more have cut great spur-end cliffs; for there can be no question that the waves of the trade-wind sea are much more powerful agents of island sculpture than the streams of short valleys and the weather changes on the valley sides. The same statement may be made for Rarotonga in the Cook group; it is elaborately dissected by wide valleys, but its embayments are replaced by alluvial plains. Its spur ends are not clift.

The Society Islands, therefore, do not support—indeed, they strongly contradict—the consequences expectable from the glacial-control theory as to the abrasion of preglacial reefs; and I believe that they likewise give no support to, if they do not contradict, the fundamental postulate of the "long period of nearly perfect stability for the general ocean floor" on which that theory is constructed; for the depth of submergence indicated by the form of the mountain slopes that inclose the embayed valleys of these islands demands a greater submergence than the glacial-control theory provides.

Furthermore, the zoölogical evidence provided by Crampton's recent elaborate investigations is so strongly confirmatory of the subsidence which earlier investigators had inferred from similar but briefer studies that the postulate of stability for these islands in particular needs revision. Crampton's conclusion is: "The occurrence of related forms [of land snails] in Tahiti, Raiatea, and Moorea means that in former times these islands were connected by land; that the common ancestral stock ranged over the whole land mass, and that its local products differentiated into the distinct species after the process of subsidence had isolated the mountains now forming the separate islands."[1]

No truncated volcanoes are known in the coral seas.—If atolls have been formed by the processes of the glacial-control theory, then after an atoll is sufficiently uplifted and dissected an abraded volcanic platform, around the margin of which the atoll reef was built up, should become visible. Most uplifted atolls are either not raised enough or not eroded enough to reveal a foundation 40 fathoms or 240 feet beneath their reef level. In eastern Fiji, however, a number of limestone islands, that I believe were formed as atolls, have been sufficiently uplifted and dissected to reveal their volcanic platform if it ever existed. In no case is it laid bare; hence, as far as these examples go they discountenance the theory. I have given details of these islands, taken chiefly from reports by Gardiner and Agassiz, in another paper.[2] There are, on the other hand, a number of uplifted fringing and barrier reefs in Fiji, and also I believe in the New Hebrides, the Solomon Islands, the Philippines, and elsewhere, which rest, as above noted, unconformably on the previously eroded slopes of volcanic or other foundations, and in which the length of the eroded slope is so great—and I believe it may be added, the volume of erosion accomplished in shaping the slope is so large—that neither the length of the slope nor the volume of the erosion can be reasonably explained as the work of subaërial destructive processes while the sea-level was lowered only 40 fathoms in the glacial epochs. All such reefs appear to me to demand subsidence for their explanation; but as they all occur in the Western Pacific, and not in the central area where only atolls prevail, they do not bear directly on the atoll problem. All that can be said of such unconformable reefs and of the uplifted and dissected atolls of Fiji is that their evidence is highly favorable to Darwin's theory, and that it is in some degree irrelevant to the origin of open-ocean atolls, which are the main subject of the glacial-control theory.

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[1] H. E. Crampton, "Studies in the Variation, Distribution, and Evolution of the Genus *Partula* . . . . ," *Carnegie Institution of Washington*, 1916, p. 296.

[2] "The Structure of High-Standing Atolls," *Proc. Nat. Acad. Sci.*, III (1917), 473–79.

As far as my reading goes only three sections have been published in which the foundation of an actual coral reef is represented as a truncated volcanic mass. One section is of the island of Mango, Fiji, as interpreted by E. C. Andrews;[1] the truncated surface is represented as covered by a now elevated coral reef into and over which later volcanic rocks are erupted; the section is reproduced as if authentic in de Margerie's translation[2] of Suess's *Antlitz der Ende;* but, as the surface of truncation is drawn below present sea-level and as the accompanying text gives no sufficient evidence of its existence, it must be regarded as hypothetical. My brief visit to the island did not enable me to examine its structure closely; but nothing that I saw gave any support to the theory of its having suffered truncation before its elevated reef was formed, nor did it appear to me that the elevated reef is older than the volcanic rocks that are associated with it. If the island really has been completely truncated, it constitutes a remarkable exception to the rule prevailing in Fiji, where the other volcanic islands have not been cut back enough to form strong shore cliffs.

A second section of a truncated volcanic island is to be found in Pirsson's account of the recent boring at Bermuda,[3] where volcanic rocks were reached at a depth of 245 feet below sea-level and penetrated to a depth of 1,278 feet. It appears to me regrettable that a single boring of this kind should be accepted as giving sufficient ground for drawing the volcanic cone with a broadly truncated surface "cut away by the action of the sea" at the depth where igneous rocks were first encountered; almost any other form would accord as well with the recorded facts; indeed, in view of the strong variations of magnetic force on the island surface,[1] it is eminently probable that the buried volcanic surface is uneven; if so, it is also probable that the depth of 245 feet is not the minimum depth of the volcanic foundation; for if the surface is uneven it is not likely that a single boring, located without any knowledge of the understructure, would reach the culminating point.

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[1] E. C. Andrews, "The General Geology of the Fiji Islands . . . . ," *Bull. Mus. Comp. Zoöl.*, XXXVIII (1900), 1–50.

[2] *La Face de la Terre,* III (1913), 1061.

[3] L. V. Pirsson, "Geology of Bermuda Island; the Igneous Platform," *Amer. Jour. Sci.*, XXXVIII (1914), 189–206.

The third example of a truncated volcanic island is Mangaia in the Cook group, which is briefly described by Marshall as having "a well-developed marine erosion surface forming the summit of the island 650 feet above sea level. An alluvial flat . . . . separates the high volcanic land from a ring of coral 125 feet above sea level . . . . 200 or 300 yards from the volcanic land."[2] This example, being visible, is better attested than the other two. It would seem to represent a volcanic cone that was completely truncated by abrasion before any reef defended it, and then elevated; but the barrier-reef ring now surrounding it may well have been formed during a later depression before a later elevation.

It is not without careful consideration that I have been constrained to reject the assumption that reef-building organisms were so completely killed during the glacial period as to leave the reefs an easy prey to the waves. The assumption is, as already noted, certainly a plausible one at first hearing, and it merits careful examination; but as the result of the best examination that I have been able to devise it proves to be erroneous. Thus a problem is laid before zoölogists: If coral reefs are today limited by temperature conditions and if the ocean were significantly cooled during the glacial period, why were not the reef-building organisms then killed? Perhaps the organisms were killed and the reefs were cut away on islands near the borders of the coral zone, as will be further considered later. Perhaps the corals were very generally killed, but the nullipores were not; if so, the nullipores, although unable to construct a reef alone, might cover and protect the exposed flanks of an already constructed reef for a geologically brief epoch until the corals could again establish themselves upon it.

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[1] J. F. Cole, "Magnetic Declination and Latitude in the Bermudas," *Terrestr. Magnetism*, XIII (1908), 49–56.

[2] P. Marshall, "Coral Reefs of the Cook and Society Islands," *Proc. Austral. Assoc. Adv. Sci.*, XIII, 1912, 140–45.

The floors of atoll lagoons.—Whatever solution the question of the survival of reef-building corals during the glacial period may eventually receive, it may be set aside for the present and return may be made to the main facts upon which the glacial-control theory is built, with the question, Is it really impossible to explain the smoothness of atoll-lagoon floors and of submarine banks without prolonged abrasion of still-standing islands? This seems to me no impossibility. Those smooth surfaces are not the result of abrasion, even if an abraded surface exists beneath them; they are the result of the even distribution of organic sediments by agencies now in operation, whatever the shape of the foundation that the sediments rest upon, as will appear from the following consideration.

As to atolls, it is true that the waters of their lagoons are generally placid, but it is also true that at times of storm they are agitated sufficiently to become turbid by stirring up the bottom sediments. Gardiner's testimony on this point, based on observations in the Maldives, is important:

> It is only in a few protected situations, where the depth is as great as 40 fathoms or more, that the lagoon bottom appears not to be churned up by the currents and waves. In heavy weather the lagoon water is almost milky, and floating surface nets [for zoölogical collecting?] are almost useless on account of the enormous amount of mud in suspension. The total amount of mud that passes out of the lagoon in the water is enormous.[1]

Hence I cannot accept Daly's statements that "the lagoon floor . . . . is little or not at all disturbed by any waves or currents generated in the lagoon itself," and that "the filling and smoothing out of the hypothetical 'moat'" about a subsiding island is little aided by the mud from the reef. "The coarser detritus" washed in from the reef flat often does "form a well-defined terrace slowly growing inward from the reef," as may be seen in many lagoons, for example, those of Tahiti and Raiatea in the Society Islands. Furthermore, as a large quantity of muddy sediment is formed on the reef flat by disintegrating agencies, organic and inorganic, acting on the blocks and scraps of coral rock washed in from the exterior reef face, and as the interior terrace of white granular detritus is free from fine silt, it follows that an important share of fine detritus from the reef must reach the lagoon floor; and this reef silt, as well as the fine organic sediments formed on the lagoon floor or in the lagoon waters, is distributed by the waves and currents therein generated, as Gardiner states.

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[1] J. S. Gardiner, "The Origin of Coral Reefs . . . . ," *Amer. Jour. Sci.*, XVI (1903), 203–13; see p. 210.

Darwin had earlier reached a fair understanding of this problem: "The greater part of the bottom in most lagoons is formed of sediments; large spaces have exactly the same depth, or the depth varies so insensibly that it is evident that no other means, excepting aqueous deposition, could have levelled the surface so equally" (26). In my own limited experience I saw the waters of two barrier-reef lagoons rolling in heavy waves under strong winds—once in Fiji, once in the broad lagoon of the Great Barrier reef off the Queensland coast—and on both occasions the water was gray with suspended sediments. It seems evident that under such conditions the finer sediments of lagoon floors will be lifted chiefly from the shallower parts and will settle in about the same amount everywhere; and the continuation of such changes will tend to produce and maintain a fairly smooth surface of sedimentation, such as actually exists.

Another view has been announced. After assigning a small value to the general distribution of lagoon sediments by the waves of gales and storms, and a large value to the distribution of sediments by currents driven under steady winds, Daly has recently reached the conclusion that lagoon floors thus aggraded during subsidence should not be level, but should be deeper to windward and shallower to leeward; then, on examining charts of atolls and verifying the general levelness of lagoon floors, he concludes that subsidence has not taken place, but that the reefs have grown up and the lagoons have been evenly aggraded in postglacial time because their sediments have been deposited on smoothly abraded still-standing platforms.[1] The conclusion does not seem tenable because the smooth floors of a good number of medium-sized atoll lagoons in the trade-wind belts have moderate depths, such as 20 or 25 fathoms, and must therefore, even under the glacial-control theory, have been aggraded by 15 or 20 fathoms if their abraded platform lies at a depth of 40 fathoms. Moreover, the fact, more fully stated in the next section, that small atolls have on the average shallower lagoons than large atolls proves that a good share of their sediments is washed in from their inclosing reefs. If aggradation by material thus partly supplied from the margin, partly from locally formed organic detritus, and distributed by trade-wind currents in the lagoons ought to produce a slanting surface of deposition, these lagoon floors should not be level; their levelness therefore contradicts the supposed necessity of slanting aggradation and confirms the theory of equable distribution and even aggradation by the lagoon waters. Hence it may be concluded that lagoon floors tend to become and to remain nearly level, whatever form the foundation of their inclosing reefs may have had, and whatever the thickness of their sediments may be; and, conversely, that the form of a lagoon floor gives no indication of the form of its buried foundation. I am therefore constrained to think that the general levelness of atoll-lagoon floors is no sufficient reason for the existence of a level rock platform at a moderate depth beneath.

The depth of lagoon floors.—If, then, the smoothness of lagoon floors is no sufficient proof of the existence of a smoothly abraded rock floor beneath them, we may next inquire as to evidence for the existence of such a rock floor that is found in the similar depth of atoll lagoons and of submarine banks. The depths are not all alike. As to atolls, Daly has shown that on the average the smaller ones are the shallower, and from this he draws the acceptable conclusion that "the smaller the platform the higher was the proportion of reef débris in the veneer, and the more rapidly has the lagoon area been shallowed" (183), and again that "the filling of the lagoon [by inwashed sediments] is in indirect proportion to the width of the platform [atoll]" (192);[1] but as this conclusion would follow equally well whether the reefs have grown up with the rising ocean around a still standing abraded platform, or in a stationary ocean around a sinking and submountainous foundation, no ground for choice between the two theories under discussion is here provided.

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[1] R. A. Daly, "A New Test of the Subsidence Theory of Coral Reefs," *Proc. Nat. Acad. Sci.*, II (1916), 664–70.

A closer scrutiny of the figures, however, reveals considerable differences of lagoon depth in atolls of about the same size, and this seems more consistent with the variable conditions offered by the theory of intermittent subsidence than with the strictly uniform conditions assumed under the theory of glacial control. For example, among 12 atolls listed in Daly's table as from 21 to 30 kilometers in diameter, the smallest value of maximum lagoon depth is little more than half the value of the largest maximum; and this smallest maximum is in an atoll the diameter of which is greater than the one which has the largest maximum. Ringgold atoll, in Fiji, is given as having a maximum lagoon depth that is more than twice as great as the maximum depth in North Argo atoll, of the same group, though both have the same moderate diameter of 10 miles. Among wide barrier reefs the one adjoining New Caledonia on the northeast has a maximum depth less than half that of the lagoon of similar breadth on the northwest of Viti Levu, in Fiji. Moreover, some lagoons reach unusual depths. In the large lagoon, just mentioned, northwest of Viti Levu, the largest island of the Fiji group, the lagoon deepens and the inclosing reef is submerged, as the distance from the island increases, in such a way as strongly to suggest recent tilting; a sounding of 59 fathoms is the maximum there recorded, but the outermost part of the lagoon has not been measured. The large lagoon of the Exploring Isles in the eastern part of Fiji deepens eastward to 80 or 90 fathoms, and this again suggests tilting, as Agassiz noted. Cases of this kind are as significant as they are exceptional. But it should be noted that many atolls of the Central Pacific are, according to the latest charts of all sources available in the Hydrographic Office at Washington, incompletely surveyed; further exploration is needed before their testimony can be used. In any case, even in atolls of similar diameter, the depths of the lagoons vary so much that they alone cannot be taken as proving that the atoll reefs have been built up with the rise of the ocean from stationary platforms of uniform depth.

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[1] The misprint "direct" in the original article is here changed to "indirect" with the author's approval.

The fact that the maximum depth of atoll lagoons seldom exceeds 40 fathoms does, however, suggest the existence of some control that has prevented the occurrence of greater depths; but this control may be found elsewhere than in the abrasion of platforms at a uniform depth below sea-level. For example, if the subsidence of an atoll or a barrier-reef island is relatively rapid, the reef will be somewhat submerged, the inwash of detritus from the reef will be active, and the increase of lagoon depth will be retarded; if subsidence is, on the other hand, relatively slow, the reef will be maintained at sea-level and will broaden its surface, sand islands will be formed along its edge, and inwash of detritus into the lagoon will practically cease; hence, in spite of slow subsidence the lagoon will not be rapidly shoaled. Thus, unless subsidence be unusually rapid, there appears to be a series of spontaneous reactions which tend to prevent lagoon depths from varying by large measures. Wherever unusually rapid subsidence occurs, the atoll would be drowned and converted into a submarine bank. The scarcity of such banks in the Pacific, as far as it is now explored, suggests very strongly that subsidence has rarely been unusually rapid; and slow, equable, or intermittent subsidence, being a near approach to long-continued stability, does not appear to be particularly incredible. But, however that may be, the known depths of atoll lagoons can be explained as well by the theory of intermittent subsidence as by the glacial-control theory. The depth of submarine banks will be discussed in a later section.

The volume of existing reefs.—The glacial-control theory suggests that a very uniform upgrowth of reefs should take place in the uniformly rising postglacial ocean, and that all existing reefs should therefore be of similar surface breadth and of similar volume. Daly finds this to be the case; he says that "the widths as well as the heights of the existing barrier and atoll reefs are of the proper size, if these calcareous rims originated on the platforms in postglacial time" (219). As to the height of reefs we know little, because the depth of their base is undetermined. Nothing is gained by assuming their base to be 40 or 50 fathoms below present sea-level, for the resulting uniformity of height has no verification. However that may be, the visible differences in the height of reefs above their lagoon floors and the breadth of reefs at sea-level seem to me too great to support the above conclusion. Yap, in the western part of the Caroline group, Western Pacific, and Rodriguez, in the Southern Indian Ocean, have broad reef plains, a mile or more in width, attached to the central islands; that of Rodriguez is 4 miles wide on the southwest side of the island. Borabora, in the Society Islands, has a barrier reef and reef flat half a mile or a mile wide, and a comparatively shallow lagoon; Mbengha, in Fiji, has a reef and reef flat of similar width around the southern side of its lagoon; the reef around Nairai, in central Fiji, is a half or a quarter of a mile wide; Budd reef, in northeastern Fiji, is narrow, generally less than a quarter-mile across, and its lagoon is 46 fathoms deep; yet near by is the long and irregular Ringgold atoll, in which the reef is half a mile or a mile wide, though the lagoon is of similar depth to that of Budd reef; Tahiti has a narrower reef, often discontinuous; Fauro, in the Solomon Islands, is fringed with a narrow sea-level reef and surrounded by a submerged bank, 70 fathoms deep in places, on which a very imperfect reef rim is found; Palawan, the southernmost member of the Philippines, is elaborately embayed along its western coast, where the headlands are neither clift nor fringed with sea-level reefs, but are fronted by a broad submerged platform, varying in depth along its length with maximum of 60 fathoms. The Marquesas Islands, nearer the equator than the numerous Paumotu atolls, have no sea-level reefs; their headlands are strongly clift, and a submerged bank extends around them. Various submarine banks have well-defined reef rims that fail to reach the surface, or that rise very discontinuously to the surface, as will be specified below; and some submarine banks are flat and rimless. Differences of these kinds in reef volume are more consistent with the unlike conditions introduced by intermittent subsidence, varying as to rate, amount, place, and date, than with the uniform conditions demanded by the glacial-control theory.

The exterior profile of coral reefs.—There is another feature of coral reefs to which Vaughan has called attention as indicating the existence of a submerged platform previous to, and independent of, the formation of the present reefs; this is the continuation of the shallow lagoon floor, not only where it is inclosed by a reef, but also through uninclosed sectors of its area where a marginal reef is wanting. A good number of examples of this kind are known in Fiji; but it is significant that the breach in the reef is in practically all cases on the leeward side. It is further significant that the uninclosed sector, which may like the rest of the lagoon floor have a general depth of 20 or 25 fathoms, slopes gradually to a depth of about 40 fathoms at its free margin and then pitches down with a steep descent to deep water; and it is still further significant that this change of declivity occurs at essentially the same depth as that at which the gentle exterior slope of the reef itself changes to a steep pitch. Instead of regarding these features as indicating the existence of a submerged platform of earlier and independent origin on which the reef was afterward built up, I am inclined to interpret both of them as resulting from aggradation by the transporting agencies of the ocean waters with respect to present ocean-level; in short, as small insular "shelves" of rapid development with respect to the present level of the ocean and therefore as corresponding to great continental shelves of long-continued development with respect to the average relation of land and sea through modern geological periods. The change of slope outside of a continuous reef will be first considered.

Darwin was, I believe, the first to suggest this view as to the origin of the exterior profile of coral reefs in his account of Keeling atoll. "As the external slope of the reef is the same round the whole of the atoll and round many other atolls, the angle of inclination must result from an adaptation between the growing powers of the coral and the force of the breakers and their action on the loose sediments" (74); and he later added, "Considering the manner in which the beds of clean coral . . . . graduated into a sandy slope, it appears very probable that the depth at which reef-building polypifers can exist is partly determined by the extent of inclined surface which the currents of the sea and the recoiling waves have the power to keep free from sediments" (84), thus foreshadowing a view that is now generally accepted.

A good number of other observers have interpreted the gradual slope and the steep pitch outside of a reef in the same way. Thus we read in the "Challenger" report regarding the reef at Tahiti, "The whole of the space from the edge of the reef to a depth of 35 fathoms was covered with a most luxuriant growth of corals, with the exception of one or two small spaces where there was white coral sand"; the steeper pitch to greater depths was covered by coral blocks, "which have been torn away from the ledge between the edge of the reef and 35 fathoms during storms, or by overhanging masses which have fallen by their own weight. In this way a talus has been formed on which the corals living down to 35 fathoms have found a foundation on which to build further seawards, for this [upper] slope is the great growing surface of the reef."[1] It may be noted that the depth here given for abundant living corals is unusually great, and that Agassiz nearly thirty years later found a smaller proportion of growing corals and a larger proportion of dead corals, coral fragments, and coral sand on the same slope; hence the population of the slope presumably varies in relation to the master-storms of decades and centuries. But the important matter to note here in the present connection is that the outer slope of the reef, like the reef itself and the prograded "belt of low land at the foot of the mountains" of Tahiti, represents an adjustment of aggrading processes and aggraded forms with respect to present sea-level, by whatever changes the present relation of land and sea-level have been brought about.

Gardiner, whose studies of reef slopes are both intensive and extensive, says of the Fiji reefs, "The section outside all is nearly the same, a gentle slope to about 40 fathoms and then a sudden steep."[2]

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[1] *Narrative of the Cruise of H.M.S. "Challenger,"* I, Part 2 (London, 1888), pp. 779, 781.

[2] "The Coral Reefs of Funafuti, Rotuma, and Fiji . . . . ," *Proc. Cambr. Phil. Soc.*, IX (1898), 417–503; see p. 445.

The same experienced observer later made a more specific statement regarding the Maldives:

> From the outer edge of an encircling reef flat there is generally to seaward a gradual slope to 30–50 fathoms in 200–400 yards, succeeded by the steep. . . . . This slope is essentially the growing area, being covered almost completely by living organisms. . . . . The outwash of detritus, largely due to undercurrents [or to general agitation by wave and current action, with the result that the finer sediments are chased about until they finally settle in deep water outside the reef where they will not be again disturbed ?], causes a raining down of coral masses and sand over the edge of the steep, carrying it out and allowing the extension of the whole outer side as a fairy ring.[1]

The growth of a reef outward, like a fairy ring, is again mentioned by the same author in his elaborate report on the Maldives.[2] A later statement by the same author is, "The steep . . . . is built up by masses of coral rock from the reef above, its angle representing that at which such material comes to rest in sea-water."[3] It is interesting to add that the change of slope on the exterior of a reef occurs at the same depth as that at which, according to Daly, "the charts of the world show the break of slope" (199) on continental shelves.

Lagoon floors of discontinuous reefs.—As to the free border of an uninclosed lagoon-floor sector, where the inclosing reef is wanting as above mentioned: It is easy to conceive that the lagoon floor there represents a more or less aggraded portion of a pre-existent platform, elsewhere inclosed by a superposed reef; and it is not difficult to explain the origin of the platform by abrasion according to the glacial-control theory as stated by Daly, or to leave it unspecified, except to say with Vaughan that it is independent of the reefs which are growing upon it. But it is also easy to conceive that the lagoon floor of today is the more or less aggraded lagoon floor of earlier days; that the lagoon floor of earlier days may have been deepened during times of rapid subsidence which caused the upgrowth of a narrow reef, or shoaled during stationary periods and periods of slow subsidence when the reef was broadened; and that the shoaling may have gone so far as to convert a narrow young reef and a deep lagoon into a mature reef plain,[1] if subsidence were long enough in abeyance. It is furthermore easily conceivable that prevalent subsidence may have been for a time neutralized in a phase of no submergence, while the ocean-level was falling as a glacial epoch came on, and then accelerated for a time in a phase of rapid submergence while the ocean-level was rising as a glacial epoch passed off; that a mature reef plain, formed during the neutralized phase of no submergence as a glacial epoch came on, might not be completely rimmed around by a new reef which grew up during the following phase of accelerated submergence as the glacial epoch passed off; and that in such case a failure of growth might reasonably enough take place on the border of the leeward sector of the reef plain, where the quantity of fine sediment shifted about by the waves might very likely prevent or retard coral growth. All of these mental schemes—mere figments of the imagination—are, as is said above, easily conceived by anyone who cares deliberately to consider the coral-reef problem; the difficulty in the problem lies elsewhere, namely, in the discovery of tests by which one of the schemes may be shown to represent better than any other the processes of the invisible past and thus to offer the best explanation for the invisible as well as the visible structures of the present.

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[1] "The Origin of Coral Reefs . . . . ," *Amer. Jour. Sci.*, XVI (1903), 203–13; see p. 211.

[2] *The Fauna and Geography of the Maldive and Laccadive Archipelagoes* (Cambridge), I (1903); II (1906); see I, 175, 182, 183, 317.

[3] "The Indian Ocean," *Geogr. Jour.*, XXVIII (1906), 313–32, 454–55; see p. 455. Also "Submarine Slopes," *ibid.*, XLV (1915), 202–19.

The best explanation that I have been able to reach is as follows. First, regarding the exterior profile of continuous reefs: In view of the evidence already given, from which it appears that the production of platforms by abrasion during the glacial period is improbable if not impossible, and in view of the fair accordance between the depths at the outer margin of the uninclosed sector of a lagoon floor and the depth on the outer face of a reef where the change takes place from a gentle slope to a steep pitch, I am persuaded that the change of slope at 40 fathoms is not an inheritance from a time when that part of the reef lay at or close to the surface of the ocean, but, as already stated, a consequence of adjustment between the detritus to be transported and the agents of transportation with respect to present sea-level. Like the reef itself, the two elements of its exterior profile—namely, the gentler slope down to 40 fathoms and the steeper pitch below—have been brought by organic growth and by inorganic processes into a normal relation to sea-level. Secondly, regarding the free border of an uninclosed lagoon-floor sector of atolls and barrier reefs: In view of the alternate retardation and acceleration of submergence by the combination of prevalent subsidence with the periodic changes of ocean-level during the glacial period—for this is, in my mind, the chief value of the glacial-control theory—I am strongly inclined to regard any "platforms" that may exist, now more or less aggraded, beneath incompletely or completely inclosed lagoon floors as nothing more than the surface of earlier reefs normally broadened while submergence was so slow that narrow reefs were transformed into mature reef plains. Thus interpreted the present reefs are merely new, still young, and relatively narrow growths above their mature predecessors; narrow, because they have been developed while submergence has been accelerated. This inclination of opinion has been strengthened by an examination of charts of submarine banks both within and without the coral seas, and that aspect of the problem must next be examined.

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[1] "The Great Barrier Reef of Australia," *Amer. Jour. Sci.*, XLIV (1917), 339–50; see p. 346.

Let it be noted, however, that if the explanation above suggested for the change in the exterior slope of a reef at 40 fathoms depth be correct, then Daly's conclusion that "the present atoll, barrier, and fringing reefs . . . . have been developed nearly or quite in the same interval of time" cannot be supported by the agreement of "their sectional areas and their volumes, as measured, in each case, above the break of slope at the platform on which the crowning reef stands" (233). A further conclusion is also vitiated, namely, that inasmuch as "the surface outcrops and volumes of the greater barrier and atoll reefs, measured from the levels of the lagoon floors, are respectively nearly equivalent in the Pacific and Indian oceans," therefore "the earth's crust must have sunk at a nearly uniform rate throughout the enormous area described . . . . if these reefs were formed by subsidence" (233, 234).

Neither the break of the exterior slope nor the level of the lagoon floor of existing reefs is, as far as I can make out, the record of a former lower sea-level: both appear to have been brought into relation with present sea-level by processes now acting. It certainly seems as reasonable to explain the exterior profile of coral reefs in this way as to explain "the break of slope on the [continental] shelves . . . . near the 40-fathom line" as a result of wave and current action at the present stand of the ocean surface, and therefore since the present stand was assumed.

[*To be continued*]